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Reflections On Steel Corrosion In Concrete

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Abstract: The paper reflects on the progress which has been made in the past twenty years in our knowledge of steel corrosion in concrete and the disparity between the current level of understanding and the state-of-the-practice. Two examples are taken from common practice: the measurement of the chloride ion content of concrete and the measurement of half cell potentials, to illustrate implications of a lack of understanding of basic principles. The paper concludes with an identification of the research needed to provide a more complete understanding of the mechanism and the factors influencing the corrosion of steel embedded in concrete.

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INTRODUCTION

In 1984, Gunnar Idorn published a paper, "A Plea for Recognition of the Impact of Chemistry on the Durability of Concrete" (1). The paper, borne of experience and frustration, develops an eloquent argument that a knowledge of chemistry needs to be incorporated in the study of concrete technology. There has been a general failure to recognize that concrete-making has moved from a craft-dominated trade to a modern industry in which reaction kinetics, thermodynamics, and colloidal chemistry are more relevant than the slump test. When discussing the need for both long term and short term approaches, Idorn makes the following axiomatic statement: "At present, under the pressure of apparently insurmountable short term problems and limited resources, attention becomes exclusively directed toward immediate needs and conventional views. This situation easily enhances reinforcement of obsolete conceptions and neglects the importance of concrete chemistry." Nowhere is this statement more applicable than in the case of the corrosion of steel in concrete.

The lack of durability of highway structures resulting from the corrosion of embedded reinforcement, and caused by the use of chloride-based deicing chemicals, first became apparent in the 1970's. This resulted in a flurry of research activity designed to develop corrosion-protection methods for new construction, as well as investigative methods and rehabilitation treatments for corrosion-damaged bridges. Many of the research studies were successful and not only raised the awareness of the need for better design, materials, and construction, but yielded epoxy-coated reinforcement, techniques for detecting corrosion, and treatments such as cathodic protection and dense concrete overlays which were suitable for application to existing bridges. However, as Idorn points out, under the pressures of public scrutiny and scarce resources, it was inevitable that the research would be directed to short term solutions at the expense of developing a basic understanding of the problem. It is ironic that many of the questions which were being asked almost 20 years ago with respect to the mechanism and the factors influencing the corrosion of steel in concrete have not been answered satisfactorily.

In recognition of Gunnar Idorn's lifetime dedication to a basic understanding of the physical and chemical phenomena in concrete technology, this paper discusses two common test methods, the measurement of the chloride ion content of concrete and half cell potential measurements, to illustrate the need for an understanding by practitioners of tools which have been commonplace for many years.

MEASUREMENT OF THE CHLORIDE ION CONTENT OF CONCRETE

Chloride Ions and Corrosion

It has been recognized for many years that chloride ions play a major role in the corrosion of steel in concrete when included in the mix ingredients or when the concrete is exposed to permeation by chloride ions in service. Since chloride ions are present naturally in many concrete-making materials, specifying a zero chloride ion content for concrete is unrealistic. Furthermore, it was known that small amounts of chloride ion in the concrete did not result in

unacceptable corrosion in the concrete and this gave rise to the concept of the chloride corrosion threshold (2). This concept inferred that there exists a chloride ion content below which the steel is "safe" from corrosion and above which, unacceptable corrosion may occur provided that other necessary conditions, chiefly the presence of oxygen and moisture, exist to support the corrosion reactions. It is important to note that while a certain minimum chloride ion content is necessary to initiate corrosion, the subsequent rate of corrosion is not controlled by further increases in the chloride ion concentration, but by other factors, principally the resistivity, pH, porosity, and availability of oxygen. This behaviour reinforced the idea that the relationship between chloride content and corrosion is a step function and that there exists a threshold value. Unfortunately, the concept is overly simplistic and the quantity of chloride ions which will depassivate the steel is not a constant, but varies with several factors, including the chemical composition of the cement (2), the ratio of the hydroxyl ion concentration to the chloride ion concentration (3,4) and, for admixed chlorides, the cation type (5).

Sources of Chloride Ion

Chloride ions may be intentionally added to the concrete, most often as a constituent of accelerating admixtures or unintentionally as a contaminant. Most cements and mixing water contain small amounts of chloride. The chloride content of aggregate varies widely, ranging from negligible amounts to values as high as 0.20% by mass. However, it is important to distinguish between chloride ions which may be on the surface or in open pores, as for example in sea-dredged aggregates and chloride ions contained within the aggregate particles and which do not dissolve in the concrete pore water.

Chloride ions may penetrate the hardened concrete in some service environments. Exposure to deicing salts, marine exposures, and conditions in some chemical plants are the most widespread examples. Chloride ions which penetrate the hardened concrete from external sources have a different effect than the same quantity added with, or contained in, the mix ingredients because a greater proportion of the former become dissolved in the pore water and contribute to depassivation of the steel. When chloride ions are added to the mix, some will combine chemically with the hydrating cement paste and others will be physically adsorbed. The amount of chloride forming chloroaluminates is a function of the C_3A content of the cement. Furthermore, chloride ions added with the mix ingredients are likely to be distributed relatively uniformly and therefore there is less tendency to cause concentration cells. Conversely, when chloride ions permeate from the surface of the concrete, the concentrations of chloride around the reinforcement are distinctly non-uniform and vary with cracking, permeability, differences in concentration on the concrete surface (because of poor drainage for example) and variations in the depth of cover to the steel.

The chloride ion content of concrete is only of indirect interest to the practising engineer because it has little effect on the engineering properties of concrete. However, corrosion becomes a major consideration when rust staining, cracking, and spalling affect the appearance and serviceability of the structure. With time, distress may occur either by loss of bond between the

steel and concrete due to cracking and spalling, or as the result of a reduction in the cross-sectional area of the steel. The latter affect is of particular concern in structures containing highly stressed high strength steel in which a small amount of metal loss might result in fracture of the steel. However, because the amount of chloride ion in concrete is a precursor of possible corrosion problems, the determination of the chloride ion content of hardened concrete is an important investigative tool and is included routinely in condition surveys of corrosion-susceptible structures.

Test Methods

There are two major issues surrounding the role of chloride ions in the corrosion of steel in concrete:

1. Determining the chloride content which will initiate corrosion reactions in the concrete in question.

2. Developing a test method which can be used to determine only that portion of the chloride ions available to support the corrosion reactions.

Once in solution, the chloride ion content is measured by a conventional titration using a standard silver nitrate reagent or by a suitable, calibrated ion-selective electrode. The titration is also normally followed by a potentiometric monitoring of the chloride ion concentration with an ion selective electrode. Test methods therefore differ principally in the method of extracting the chloride ions from the concrete and variations of two basic methods are in common use: digesting in nitric acid and dissolving in water. An alternative approach is to extract the pore water by applying high pressure to the concrete, though this method requires equipment available in only a small number of laboratories.

The standard acid-soluble test method is AASHTO T 260 "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials" (6). A representative sample is ground to pass a 300 μm (#50) sieve. The chloride ions are extracted by digestion in nitric acid and then measured by a titration.

A water-soluble test method, also specified in AASHTO T 260, is very similar to the acid-soluble method. However, the rate of dissolution in water is affected by the extraction time, the temperature of the water and the particle size, and these must be carefully controlled. As a consequence, the measured value is a function of the test method. The chloride ion is extracted by boiling in water for 5 minutes and then allowed to stand at room temperature for 24 hours prior to analysis of the aqueous phase. The water soluble test came into general use because some procedures were quicker than the acid extraction and it was thought that the result of the test represented the quantity of chloride ions which was available to support corrosion and this myth has been perpetuated for many years.

Several years ago, the Ontario Ministry of Transportation modified the AASHTO T 260 test method (7). A representative sample is first ground to pass a 300 μm (#50 sieve) as specified in AASHTO T 260. A weighed portion is then

transferred to a mortar and further ground as a slurry before analysis. The final sample should completely pass a 150 μm sieve (#100) and 75 percent should pass a 75 μm (#200) sieve.

Based on the work of Lewis (8), further studies at the Federal Highway Administration Laboratories in the early 1970's (9) showed that for hardened concrete subject to externally applied chlorides, the corrosion threshold was 0.20 percent acid-soluble chloride ions by mass of cement. The average ratio of water-soluble to acid-soluble chloride ions was reported to be 75 to 80% (10), although the original work (11) indicates an average of 77% for chloride ions added at the time of mixing and 87% for chloride ions which permeated the hardened cement paste specimens. Extraction was by boiling followed by 48 hours standing at room temperature. A figure of 75% has been widely used to convert acid-soluble to water-soluble chloride ion contents, regardless of the extraction procedure and the source of the chloride ions.

Aggregates in Southern Ontario

The confusion surrounding the availability of chloride ions in concrete to support corrosion reactions and the relationship between water-soluble and acid-soluble determinations can be illustrated by examining the situation of commercial aggregates in Southern Ontario.

The most common high-quality aggregates in Southern Ontario are crushed dolomites from the Amabel and Lockport formations which form the cap rocks of the Niagara Escarpment. These rocks contain unusually large amounts of chloride ion as a result of their deposition in a saline environment on the fringes of the Michigan Basin. The acid-soluble chloride contents of aggregates supplied to the Toronto area from the Amabel formation was found (12) to be 0.125% (average of 25 samples) and from the Lockport formation 0.080% (average of 5 samples). For typical concrete mixtures, these aggregates would contribute more than the threshold value for corrosion to the concrete if all the chloride ions dissolved in the pore water.

Figure 1, which has been compiled from data in a 1977 report (12), compares the acid soluble and water soluble chloride contents of aggregates from 24 quarries and one pit in Ontario, of which 23 sources were either dolostones or limestones. The water soluble chlorides were extracted by grinding the rock samples to pass a #100 mesh screen and then boiling the rock powders in water for five minutes. The ratio of water soluble to acid soluble chloride ions ranged from 0 for a number of limestones to 75% for a beach gravel. Extremely high chloride contents were measured on all the samples from the Amabel formation.

A small test was conducted in the Ministry's laboratories in 1975 on a sample of aggregate from the Amabel formation using particles in the 19 to 26 mm range. The stone was immersed in distilled water for a period of 90 days and the chloride ion content of the water measured periodically. The measured chloride content was 0.003 percent after one day and this did not increase over the 90 day period, indicating that the likely source of chloride ions was the exposed

particle surfaces and that chloride contained within the aggregate did not enter into solution. The rock in question is porous (about 2% absorption) and the pores are of a very large size and poorly interconnected.

In a 1982 experiment, samples of different particle sizes of the same aggregate as in the 1975 test, ranging from retained on 19 mm to passing 53 μm, were prepared and immersed in water for one week. The samples were agitated periodically. After 7 days, the chloride ion content of the water was determined and the results are shown in Figure 2. As the particle size decreases, the chloride ion content increases and the relationship is almost linear when plotted on a log/log graph. In other words, as the rock is crushed to expose a greater surface area, the measured chloride ion content increases. However, as the preliminary experiment carried out over a longer period indicated, the chloride ions are unlikely to enter into solution and contribute to corrosion. This means that the measured chloride content is a function of the test method, specifically the preparation of a pulverized sample, and not a measure of the chloride ion available to depassivate the steel.

In interpreting data from concrete samples, it is therefore necessary to correct for the background chloride ion content of the concrete when using aggregates with high, but "unavailable" chloride ion contents. This has usually been done within the Ontario Ministry of Transportation by taking concrete cores sufficiently deep into the concrete that there is only a remote possibility that the concrete has been exposed to external sources of chlorides. The chloride content of the concrete most distant from the exposed surface is then taken as the "background" value, provided it checks with the historical value, and subtracted from all the measured values before making an assessment of the likelihood of corrosion (13). This approach would not be valid if chloride-based admixtures had been used in the concrete. The presence of such admixtures would normally be evident from abnormally high chloride-ion values which did not diminish with distance from the exposed surface. The chloride ion content of the aggregates from the five quarries extracting rock from the Amabel formation and serving the Toronto market has been checked over a period of years and found to be very uniform (typically 0.125% acid soluble and 0.041% water soluble). Laboratory mixes have indicated that the aggregate is responsible for over 75% of the background chloride value. This means that anticipated background values can be as high as 0.07% for acid soluble measurements and 0.020 to 0.025 for water soluble determinations.

The subtraction of background values is an "engineering" approach in the absence of a test method to measure only the chloride ion content available to initiate corrosion. However, it should be noted that its validity has been verified by rate-of-corrosion measurements on laboratory specimens (14) and by observations in the field.

Research to Identify a New Test Method

In view of the absence of a test method to measure the "available" chloride ion content of concrete, and the particular situation of chloride-bearing aggregates in Southern Ontario, the Ministry of Transportation sponsored research at Queen's University at Kingston to investigate existing test methods and

develop a more discriminating procedure (15). Most of the work was concentrated on procedures for extracting the chloride ions with water.

Extraction Procedures--A number of different procedures were investigated for extracting the chloride ions with water.

Three variations of cold water extractions were used: unstirred (CW), and stirred continuously (CWS). In addition, concrete samples were sliced 6 mm thick and broken into large pieces. These pieces were also stirred continuously (CWP).

Two variations of hot water extractions were used, 15 minutes of boiling followed by 18 hours standing at room temperature (HW) and fractured pieces maintained in water at 80°C and stirred continuously (HWP).

Chloride ions were also extracted using a Soxhlet extractor containing 100 ml of water. Slices of concrete, 6 mm thick were fractured to give 12 mm pieces in 30 g lots. The heat input was sufficient to give a cycle of about 3 extractions per hour. The extraction was essentially complete in 24 hours and further extraction did not yield a further significant quantity of chloride ions.

Analysis of Constituent Materials--A first series of tests were carried out on the following raw materials: a Type 1 Normal Portland Cement, water, a natural siliceous sand fine aggregate. The acid soluble chloride ion contents were 0.020%, <0.001% and 0.010% respectively. Three coarse aggregates: a limestone with a low chloride ion content and two dolostones, one high in chloride ions and the other having an intermediate chloride ion content, were subjected to several extraction procedures. The results are given in Table 1.

Table 1: Analysis of the Chloride Content of Coarse Aggregate

	Chloride Content, % by Mass		
	Aggregate #1	Aggregate #2	Aggregate #3
Acid Soluble	0.010	0.136	0.197
Hot Water Extractions			
HWP, 12 mm, 8 hr.	<0.001	<0.001	<0.001
HW, 300 μm, 18 hr.	0.005	0.038	0.065
HW, 37 μm, 18 hr.	0.013	0.095	0.155
Sox, 12 mm, 24 hr.	<0.001	<0.001	<0.001
Sox, 12 mm, 7 days	<0.001	<0.001	<0.001

The results show that immersing the aggregate particles in hot water did not remove measurable amounts of chloride ion. Even a continuous 7 day extraction in the Soxhlet apparatus did not remove measurable chloride. When the particles were pulverized to pass a 300 μm (#50) sieve, a significant portion of the chloride ions entered into solution. However, when the pulverized material (before extraction) passing a 300 μm sieve was placed in a shatter box such that at least 50 percent of the powder passed a 37 μm (#400) sieve, the amount of chloride extracted increased substantially. The specific surface of the material passing the 300 μm was calculated to be 435 cm^2/g, and 780 cm^2/g after further

grinding in the shatter box. These results not only confirm the effect of particle size on the measured value of chloride ion illustrated in Figure 2, but also indicate why large differences in results can be obtained from identical tests, except that in one case, the powder is ground finer than in the other.

Concrete Samples--The following concrete samples were prepared with a water-cement ratio of 0.40:

C1 - concrete with low chloride aggregate #1
C2 - concrete with medium chloride aggregate #2
CC - concrete with aggregate #1 and 2% calcium chloride dihydrate (by mass of cement) added to the mixing water
CS - concrete with aggregate #1, vacuum saturated with 3.5% by mass of aqueous sodium chloride.

The specimens were cast as 100 x 200 mm cylinders and cured for 28 days. The CS specimens were oven dried and vacuum saturated after 28 days.

A similar series of tests to that performed on the constituent materials was undertaken and the results are summarized in Table 2.

Table 2: Analysis of the Chloride Content of Concrete Samples

	Chloride Content, % by Mass			
	C1	C2	CC	CS
Acid Soluble	0.014	0.073	0.216	0.113
Cold Water Extractions				
CWP, 12 mm	0.002	0.002	0.046	0.045
CW, 300 μm, 18 hr.	0.008	0.012	0.119	0.068
CWS, 300 μm, 18 hr.	0.013	0.044	0.175	0.099
Hot Water Extractions				
HWP, 12 mm	0.002	0.002	0.082	0.045
HW, 300 μm, 18 hr.	0.006	0.019	0.184	0.102
HW, 37 μm, 18 hr.		0.055	0.199	
Sox, 24 hr.	0.004	0.003	0.169	0.102

The hot and cold water extractions from the 12 mm size fragments yield only a small fraction of the acid soluble chloride ions and do not extract chloride ion from the aggregates. A larger proportion was measured in cold water when the concrete was pulverized to pass a 300 μm (#50) sieve and the quantity was increased substantially by stirring continuously. The hot water extractions demonstrated the same effect of particle size as did the pulverized aggregate samples, i.e. as the sample is ground finer, a greater amount of chloride ion is extracted from chloride-containing aggregates. The Soxhlet extraction was found to discriminate between the chloride ions contained in the aggregates (mixes C1 and C2) and that added with the mix water (CC) or infiltrated into the hardened concrete (CS).

Since concretes CC and CS are the same as concrete C1 with the addition of calcium chloride and vacuum saturation with sodium chloride respectively, the

contribution from the calcium chloride and the sodium chloride can be calculated as shown in Table 3.

Table 3: Proportion of Added Chloride Ions Removed by Soxhlet Extraction

	Chloride Content by Mass, %	
	Chloride Ion Added as $CaCl_2$ (CC-Cl)	Chloride Ion Added as NaCl (CS-Cl)
Acid Soluble	0.202	0.099
Sox, 24 hr.	0.165	0.098
% Added Chloride Removed by Soxhlet	82	99

The results show the difference in availability between chloride ion added at the time of mixing and that which permeates the hardened concrete, and the ability of the Soxhlet apparatus to distinguish between the availability of the two sources.

Four major results emerge from the studies of chloride ion measurements reported here:

1. Conventional acid soluble and water soluble tests extract chloride ions from aggregates which do not participate in the corrosion reactions in concrete and only become available when the aggregate is pulverized.

2. The results from water soluble tests are affected significantly by the particle sizes of the pulverized specimen.

3. Large differences in water-soluble chloride ion contents can be measured in two tests, both carried out in accordance with a standard test method (AASHTO T 260 for example), simply by grinding the powder finer in one case than the other.

4. The Soxhlet extraction procedure has the capability to discriminate between chloride ions which are available to the corrosion processes and those which are unavailable by virtue of being contained in the aggregates or chemically bound in the cement paste.

The idea of using the Soxhlet extraction technique is not new; it was suggested by Berman (11) many years ago but not pursued because of the apparatus and time required for one determination. The work reported here is not intended to suggest that the technique become an everyday test method because, where chloride ion contents are low or background levels are small, existing techniques are quicker, less expensive and adequate. Even where high levels are recorded, engineering approximations, when combined with local knowledge, often suffice. However, where uncertainty exists, or there is a need for a more discriminating procedure, the Soxhlet method is very useful.

HALF CELL POTENTIAL TESTING

The other common test method which is often either misused or misinterpreted is the half cell potential test. This test was first applied in a systematic manner to reinforced concrete structures by Stratfull and his co-workers (16,17). The test evolved into ASTM C 876-77 (now ASTM C876-87).

In a half cell survey, a standard reference cell is placed on the surface of the concrete and the potential compared with the potential of the embedded steel. A copper-copper sulfate (CSE) cell is most commonly used in North America. A high impedance voltmeter is used to eliminate IR effects and one terminal is connected to the half cell and the other to the reinforcing steel. A damp sponge is usually used to obtain good electrical contact between the cell and the concrete. The circuit is completed provided the concrete is sufficiently moist.

Working on laboratory specimens, Stratfull (18) found that measurements of half cell potentials identified steel that was:

i) corroding or active, if the potential was less (more negative) than -0.35 V (CSE)

ii) not corroding, or passive, if the potential was greater (less negative) than -0.30 V (CSE).

These values were subsequently modified by Clear (19) as follows:

i) For readings more negative than -0.35 V (CSE), there is a high probability that the steel is corroding at the time of measurement.

ii) For readings in the range -0.20 V to -0.35 V (CSE), the corrosion activity of the steel is uncertain.

iii) For readings less negative than -0.20 V (CSE), there is a high probability that the steel is not corroding.

Confirmation of the empirical relationship between half cell potentials, corrosion activity, and corrosion-induced distress was established in a number of field investigations (17,20-22) and the interpretation of the measured values by Clear was included in ASTM C 876-77.

The measurement of half cell potentials filled a previously unsatisfied need for a quick, non-destructive method of assessing reinforced concrete structures for corrosion and became a routine element of most condition surveys. Unfortunately, a number of the basic principles of the method have been overlooked on occasion with the predictable result that measured values have been meaningless, or misinterpreted, or both.

A half cell potential survey requires a connection to any steel which is not electrically continuous. While the steel in most highway structures is continuous, this is often not the case for structures such as parking garages.

The concrete must be sufficiently moist to complete the electrical circuit. A wet sponge will usually suffice in an outdoor environment, but this is not necessarily the case in the interior of enclosed buildings. Probably the most serious misuse of half cell condition surveys is in the interpretation of the data, since it is often forgotten that the interpretation is based on an empirical relationship developed from observation on bare steel embedded in concrete and subjected to periodic wetting and drying in an outdoor environment. This has not prevented the test being used on dry concrete in the laboratory, saturated concrete in the fog room, coated reinforcement, embedments of mixed metals, and similar inappropriate applications, even though the latest edition of ASTM C 876 (23) specifically limits the scope to uncoated steel in concrete.

An example of the possibility of misinterpretation which can arise when half cell potential measurements are applied outside the scope of the test method is illustrated in a survey, conducted in 1988 (24), of the performance of epoxy-coated reinforcement in Ontario. The purpose of the study was to determine whether epoxy-coated reinforcement, which had been introduced in Ontario in 1979, was an effective corrosion-protective treatment. A worst case experimental design was adopted and, since all bridge decks are waterproofed, the investigation was limited to barrier walls, and specifically to barrier walls which contained the highest amount of chloride ion at the level of the reinforcement. Sections of two reinforced concrete barrier walls constructed in 1979 with epoxy-coated reinforcement were thoroughly investigated. For comparison, sections of wall with uncoated reinforcement, which was similar in all aspects of concern to the sections with coated bars, was also investigated. Numerous observations and tests were carried out (24), but the purpose of this summary is to report only the results of the half cell potential tests. The limitations of the technique were recognized, but the test was included to determine if anomalous situations could be identified and for comparison with other similar studies.

For the sections with coated bars, a connection was made to each reinforcing bar, in turn, because of the lack of electrical continuity between the bars. The bars in the section with black steel were verified to be electrically continuous. A summary of the readings is given in Table 4.

Table 4: Summary of Potential Measurements on Three Barrier Walls

Bridge No.	Steel	No. of Readings	% of Readings		
			>-200 mV	-201 to -349 mV	<-350 mV
100140B	Epoxy	112	10	45	45
240319	Epoxy	122	13	76	11
100285	Black	98	0	29	71

The highly negative potential readings for Bridge 100285 were consistent with the visual observations of rust staining and the measurement of the rate-of-corrosion (by linear polarization) and the chloride ion content of the concrete at the steel. The two bridges with the epoxy coated reinforcement

exhibited a substantial number of readings more negative than -200 mV (CSE) and for Bridge 100140B, almost half the readings were more negative than -350 mV (CSE). For Bridge 240319, concrete was removed in the test section which was the full height of the wall and approximately 1.2 m long, to permit a detailed examination of the coating. The coated steel was found to be in good condition and the only evidence of corrosion activity was found on a hairpin stirrup in the top of the wall and the damage was consistent with that which would result from an impact on the bar before the concrete was placed. Cores were taken from Bridge 100140B along a wide crack which extended the full height of the wall and permitted the access of deicing salts directly to the reinforcement. The epoxy-coated steel contained in the cores was in good condition and exhibited no noticeable deficiencies. The highly negative potential measurements were inconsistent with the visual observations and an explanation based on the principles of half cell measurements was sought.

Different corrosion situations can be visualized by plotting, on the same graph, the log of the absolute current (I) versus potential (E) curves which would be obtained by polarizing each half cell with an auxiliary counter electrode in the absence of the other half cell, as shown in Figure 3. The rest potential or open circuit potential of the corroding sample will be that at which the two curves intercept. At this point no net, external current flows, and the absolute value of the current at the intercept is equal to the corrosion current ($Icorr_1$). $Ecorr_1$, measured by a reference cell, is the mixed potential of the anode and cathode. If the cathodic process is slower (the one with the large polarization), the corrosion rate is considered to be cathodically controlled which is the case illustrated in Figure 3 and the usual case for steel in concrete. The most probably explanation of the high potentials of the coated reinforcement without corrosion is that the coating restricts the access of oxygen to the steel surface. This slows the cathodic reaction with the result that the cathodic polarization increases and the slope of the cathodic curve approaches infinity. The mixed potential measured by the half cell ($Ecorr_2$) then approaches the anodic potential of the corrosion cell which is likely present at a holiday or break in the epoxy coating. At the same time as $Ecorr_2$ becomes more negative, $Icorr_2$ is reduced which explains why small corrosion currents can be associated with highly negative potential readings.

CONCLUDING REMARKS

Gunnar Idorn has always appealed for a basic understanding and a long term commitment to the resolution of problems in concrete technology. Faced with the realities of funding for research, it is inevitable that a short term view will dominate and expedient solutions be sought. Corrosion-related research over the past 20 years has made significant advances, but many of the fundamental questions remain. These include:

i) What is the mechanism of the depassivation of steel in concrete?

ii) What quantity of admixed or permeated chloride ions will initiate corrosion of steel in concrete?

iii) What levels of relative humidity and oxygen concentrations are required to sustain corrosion reactions?

iv) What are the quantitative effects of the factors which determine the rate of corrosion of steel in concrete?

v) What are anticipated service life of corrosion protection treatments applied to new and existing structures?

It would be interesting to speculate how different the state-of-the-art would be today if we had followed Idorn's credo and initiated basic research to answer the above questions some twenty years ago.

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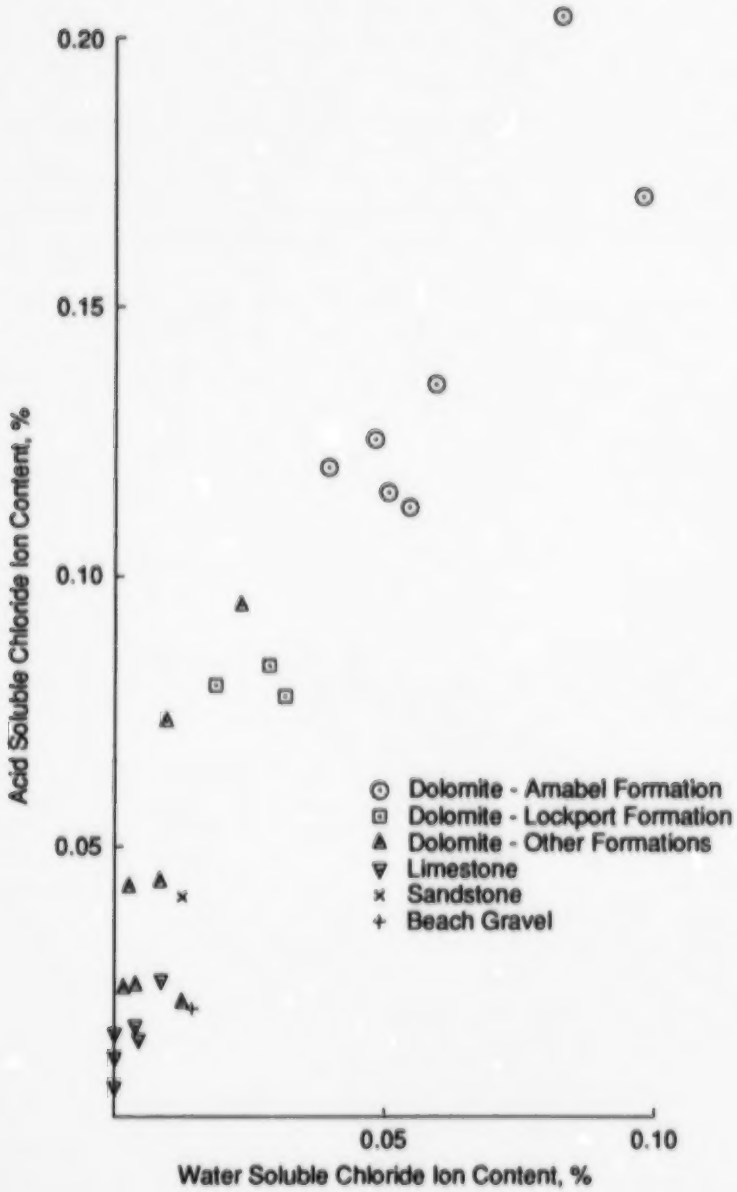

Figure 1/ Comparision of Acid-Soluble and Water-Soluble Chloride Ion Contents of Commercial Aggregates from Southern Ontario

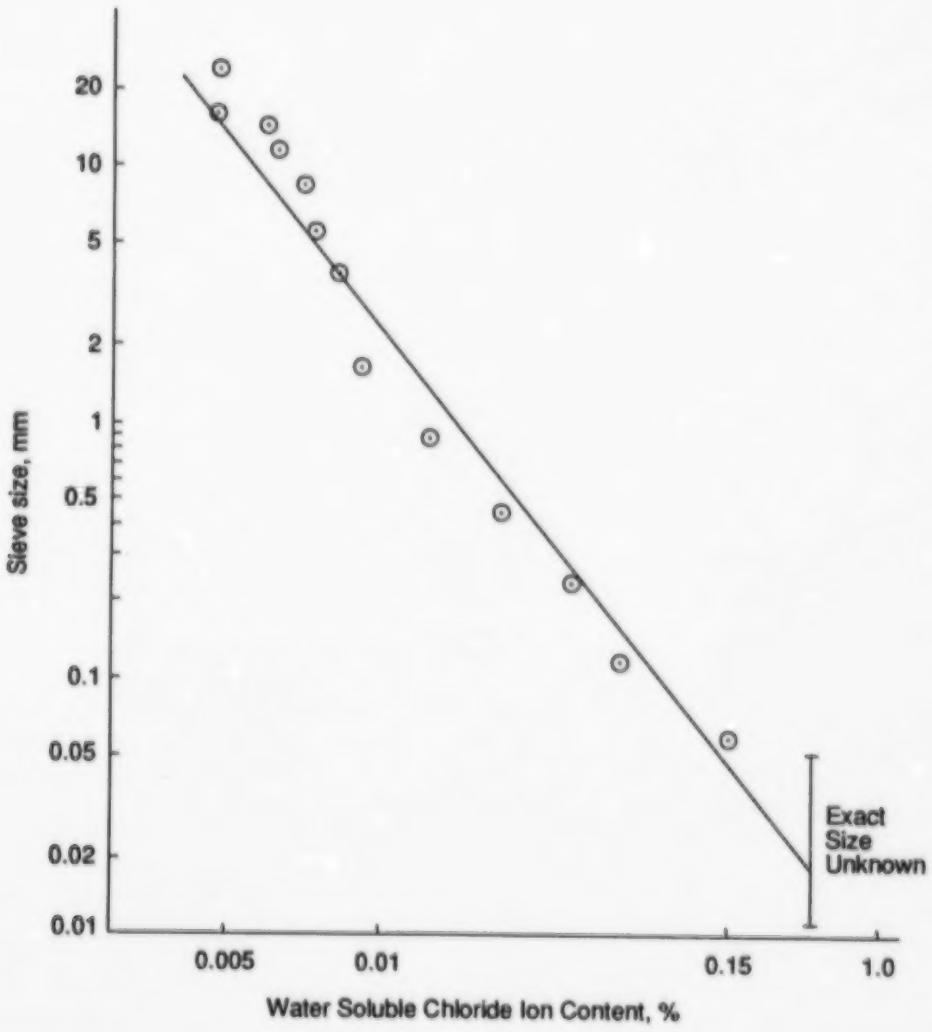

Figure 2/ Effect of Particle Size on Measured Water-Soluble Chloride Ion Content

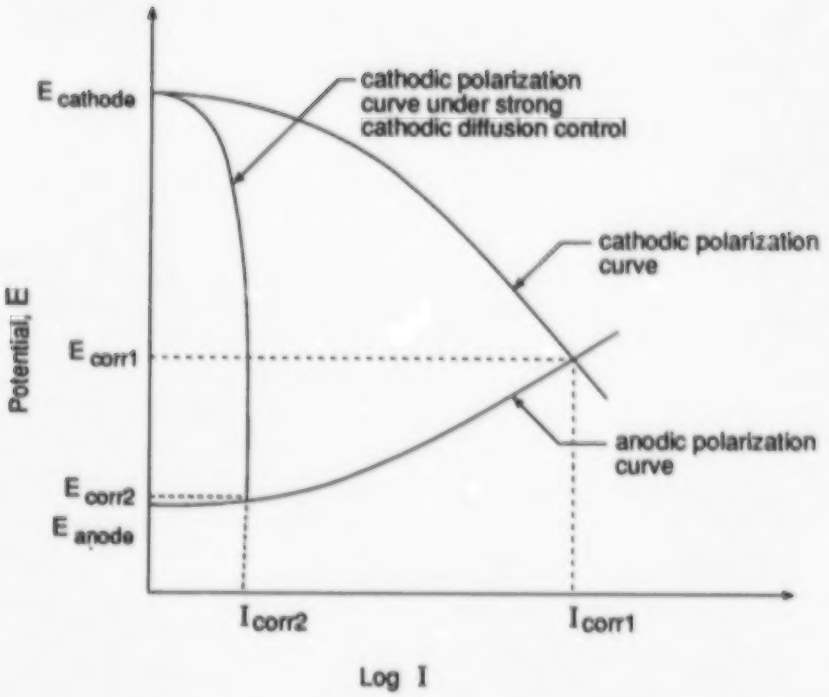

Figure 3/ Corrosion Cell Under Cathodic Diffusion Control